# *Spin Measurements in Events with Missing Energy at the LHC*

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*(arXiv: 1004.xxxx)*

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# *Outline*

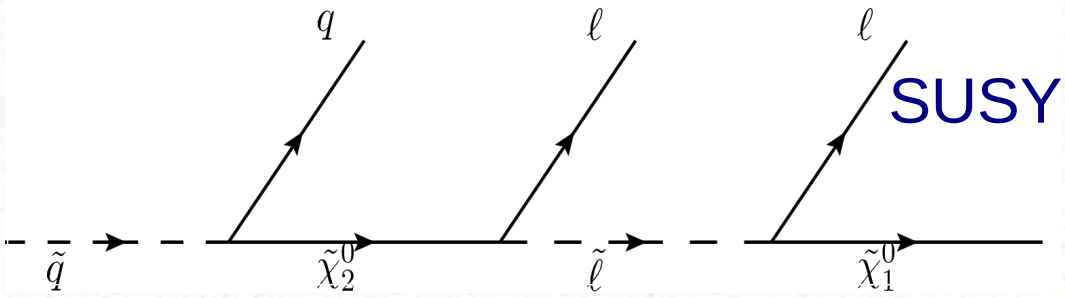
- Motivation
  - Spin determination important but difficult in events with missing energy
  - Existing methods have their limitations
- Obtaining spin correlation from event reconstruction
  - Single-chain case *vs* double-chain case
  - Under-constrained/solvable/over-constrained system
- Conclusion and outlook

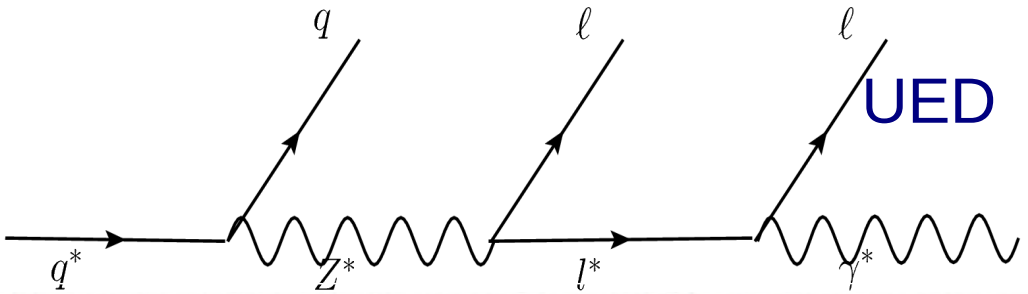
# *Models with missing energy signature*

- SUSY (R-parity), UED (KK-parity), Little Higgs (T-parity)...

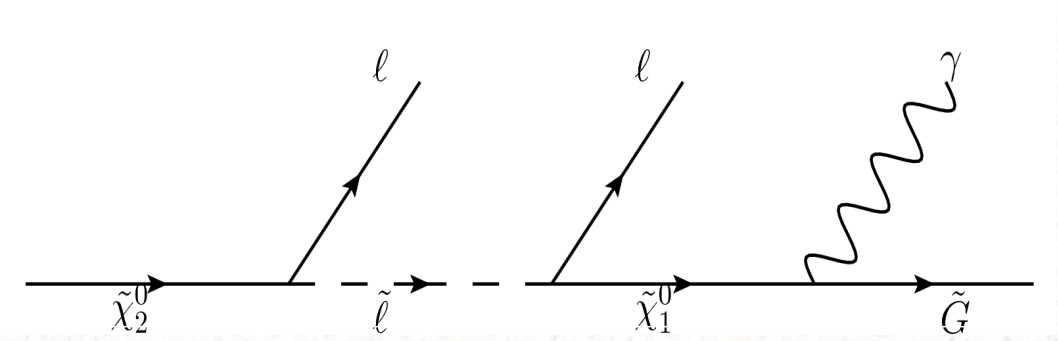
  Example process: $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\ell}\ell \to q\ell\bar{\ell}\tilde{\chi}_1^0$

- Hard to reconstruct the kinematics due to two (or more) missing particles.

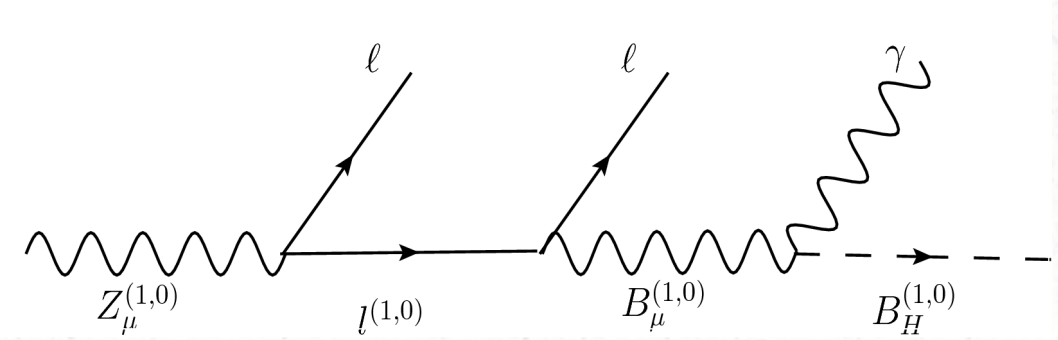


# *Another example*




Gauge mediation



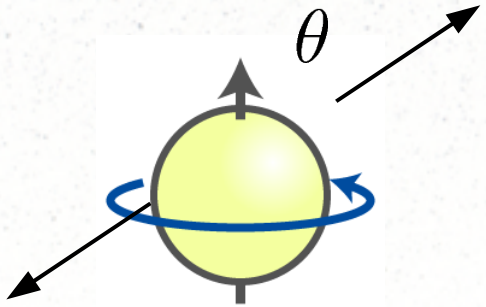

6D UED (*Burdman, Dobrescu, Ponton; Dobrescu, Kong, Mahbubani,*),
$B_H^{(1,0)}$ : scalar “KK-photon”
Similar process in PQ-UED (*Csaki, Heinonen, Hubisz, Shirman*)

# *What's the theory?*

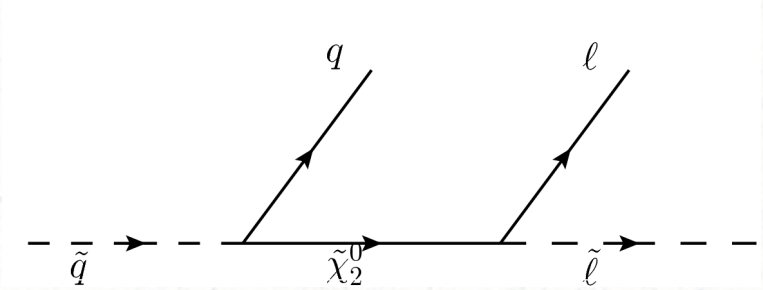
- Mass determination
- Spin determination
  - Cross-sections depend on spin
  - Kinematics: $p_T$
  - Invariant mass method
  - Event reconstruction method
    - Easier for e+e- machine (Buckley, Murayama, Klemm & Rentala)
    - Focus on LHC in this talk

# *Angular distribution of decay products*

- Non-uniform angular distribution of decay product:
  - Polarized mother particle.
    - Helicity basis: reference direction is its own momentum
  - For fermions: chiral coupling for the decay.
- The angular distribution is a polynomial of $\cos\theta$ of order 2*Spin. $\theta$: defined in the rest frame of mother particle

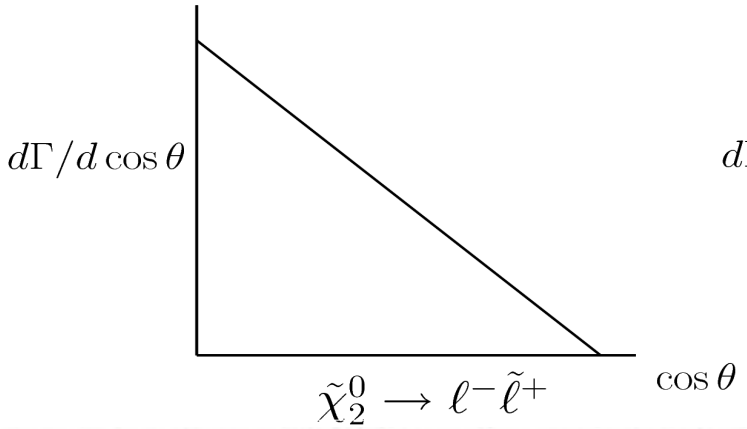


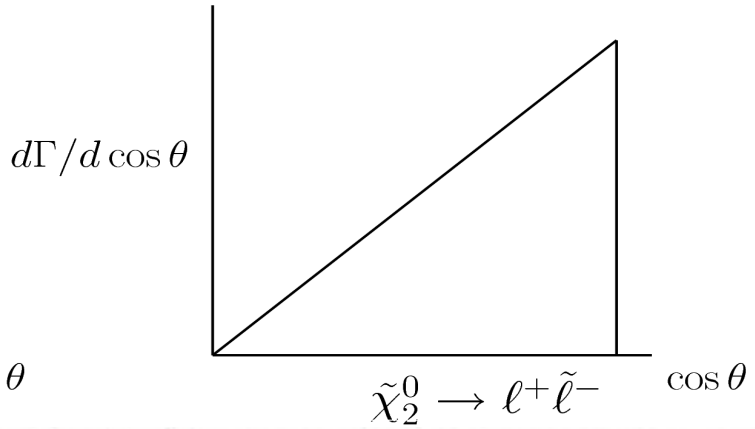
# An example




$$\tilde{q} \to q_L \tilde{\chi}_2^0 \to q_L \ell_R \tilde{\ell}_R$$

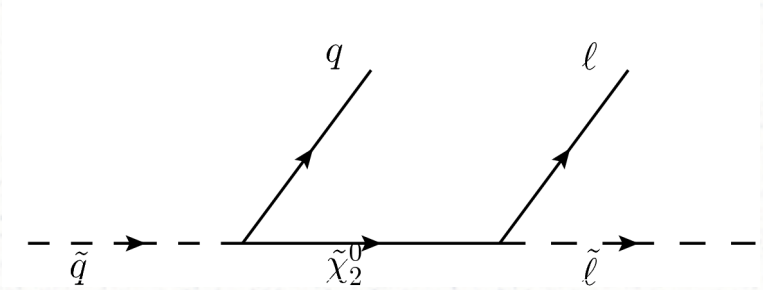
- Both couplings are chiral. Neutralino is left-handed in the rest frame of squark.
- The lepton (anti-lepton) is right (left)-handed, which tends to anti-align (align) with the neutralino momentum.

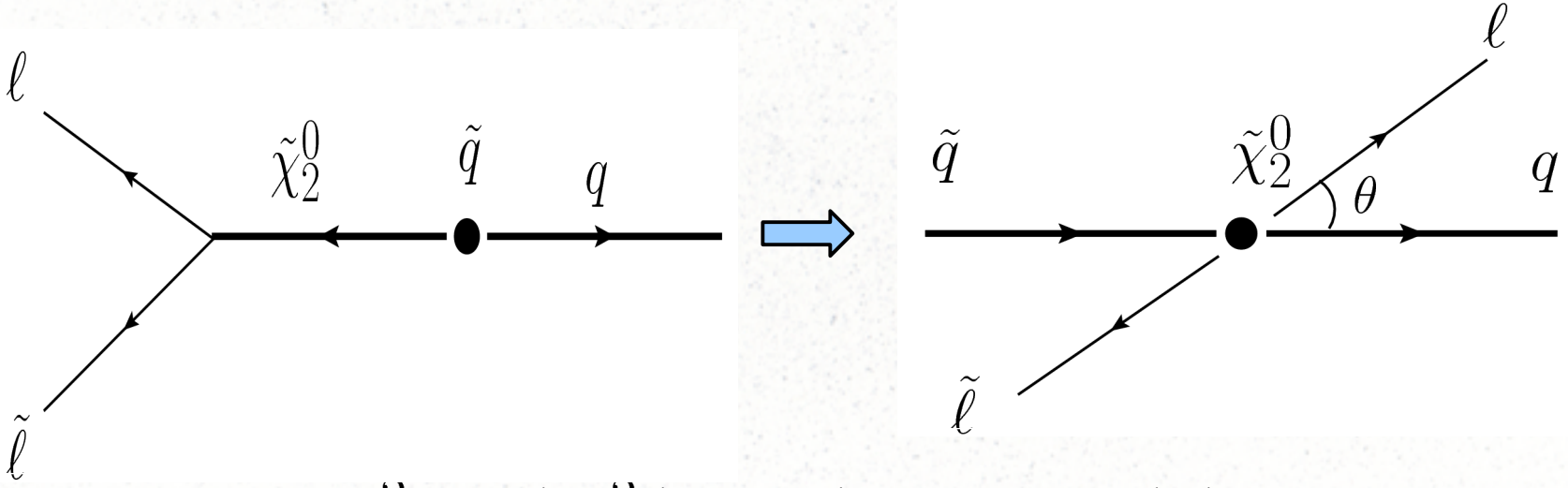



$\theta$ : Angle between lepton and neutralino, in rest frame of neutralino.

# Relation to invariant mass



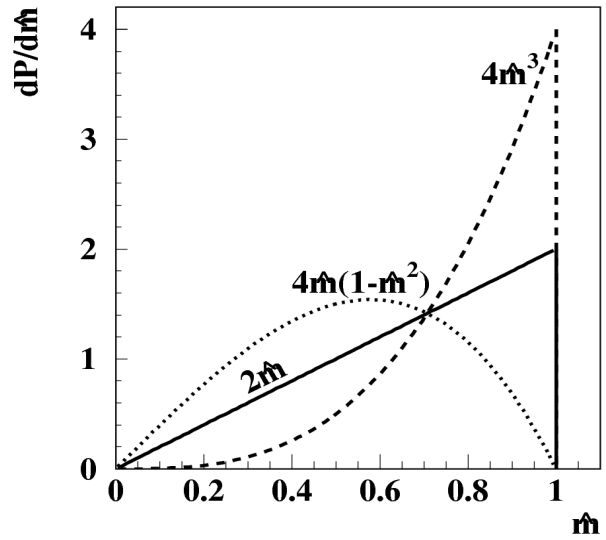



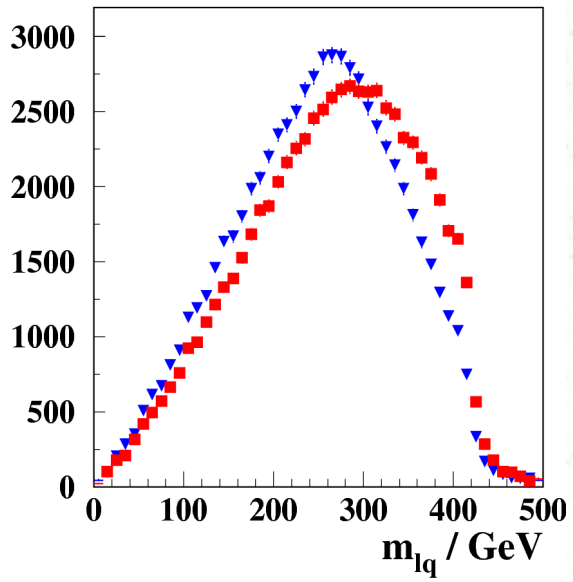

$$m_{ql}^2 = (m_{ql}^2)\max(1 - \cos\theta_{ql})/2$$

$$\cos\theta(\tilde{\chi}_2^0, l) = -\cos\theta_{ql}$$

# *The invariant mass method*

- SUSY case, parton level, invariant mass of quark-lepton (Alan Barr).
  - Can't distinguish near and far lepton
  - Don't know charge of squark, but LHC is proton-proton: charge asymmetry




Red: l+
Blue: l-

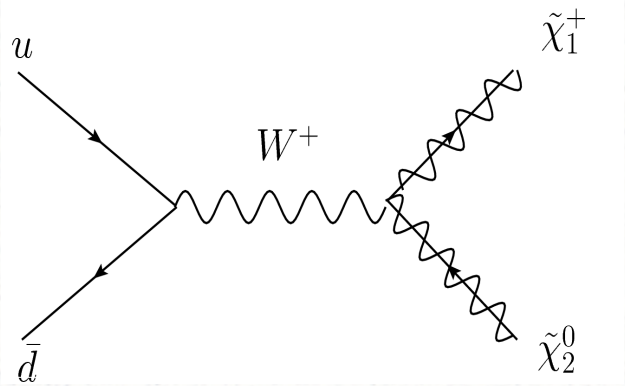
# *More studies using inv. mass*

- Jennifer M. Smillie, Bryan R. Webber , 2005 (UED vs SUSY), 2006
- Can Kilic, Lian-Tao Wang, Itay Yavin, 2006, 2007
- Michael Burns , Kyoungchul Kong , Konstantin T. Matchev, Myeonghun Park, 2008
- Wolfgang Ehrenfeld, Ayres Freitas, Ananda Landwehr, Daniel Wyler, 2009 (events with photons)
- .....

# *Limitation of inv. mass methods*

- The invariant mass distribution of two adjacent visible particles measures the spin of the particle in between.
- Can we measure the spin of the first particle in the decay chain?
  - It needs to be polarized
  - Need to reconstruct its momentum

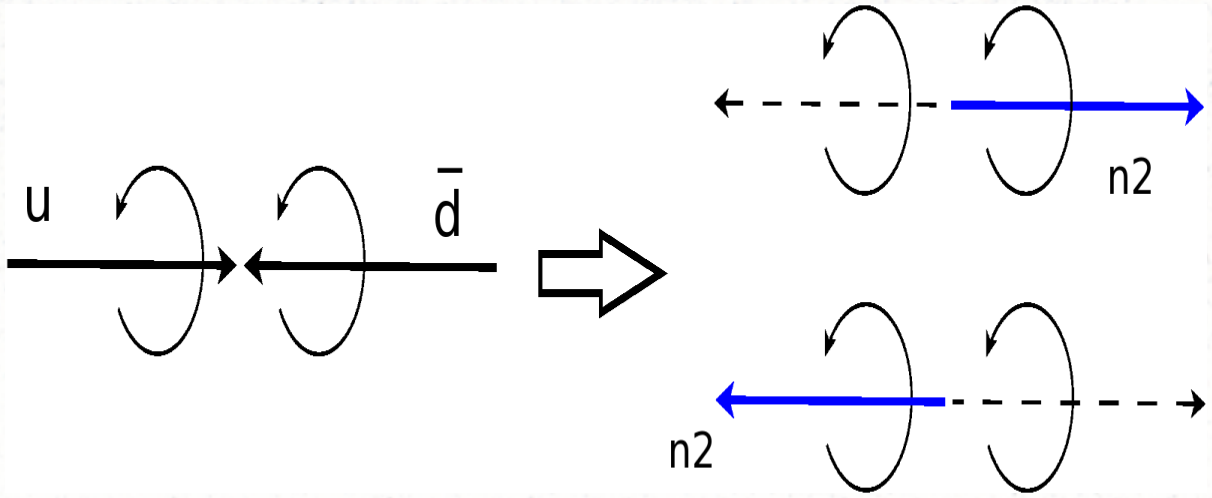
# *Chargino/neutralino production*



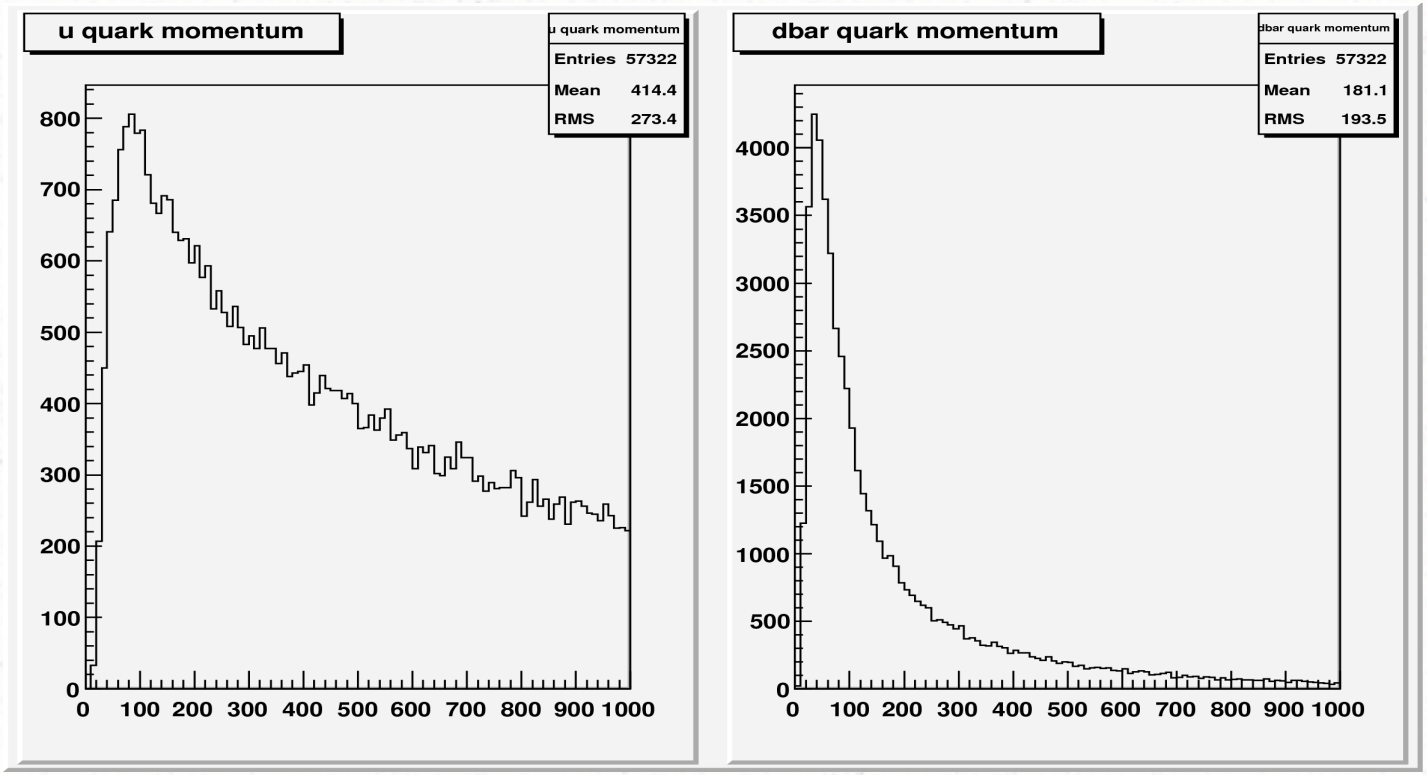

- Similar for KK-Z/KK-W production  in UED
- Significant cross-section ~1 pb for 180 GeV Neutralino/chargino, ~10 pb for KK-Z/KK-W. clean signature: lepton/tau.
- Neutrlino is polarized (in the lab frame)

# *Why is neutralino polarized?*

- Dominated by W boson exchange if squark heavy.
- Incoming up quark left-handed, dbar right-handed.
- Neutralino left-handed if aligned with up quark, right-handed if anti-aligned, equal probability in *center of mass frame*.



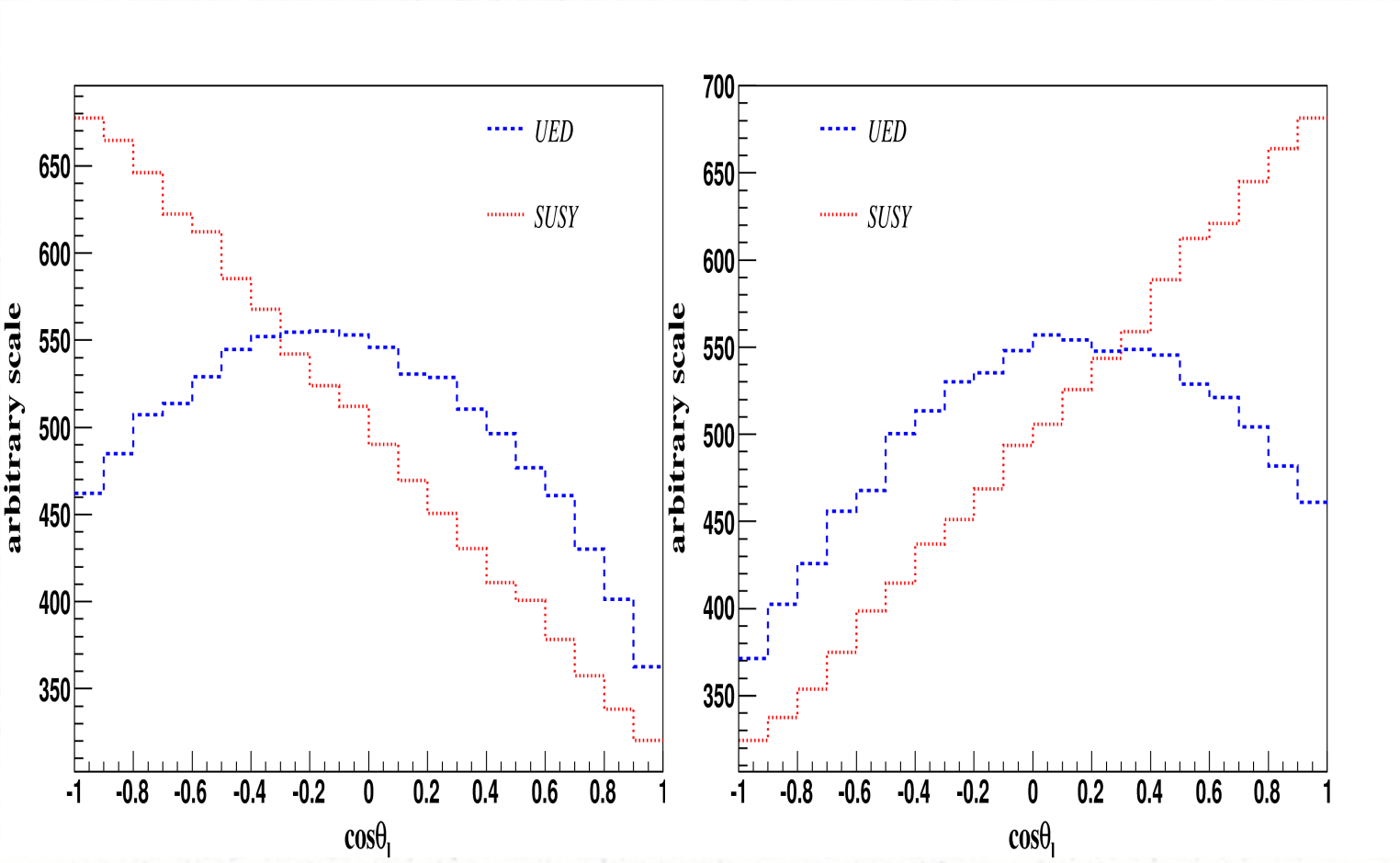
# *Incoming parton momenta*



# *Polarized neutralinos*

- The whole system boosted along up quark direction, changing some right-handed neutralinos to left-handed: more left-handed neutralinos.
- Similar for KK-Z/KK-W.
- Polarized neutralino further decay to lepton+slepton through a chiral coupling: non-trivial angular distribution for near leptons.

# *Polarized neutralino/KK-Z decay*




"near"-lepton angular distributions.
Need to reconstruct neutralino momentum. Possible? How?

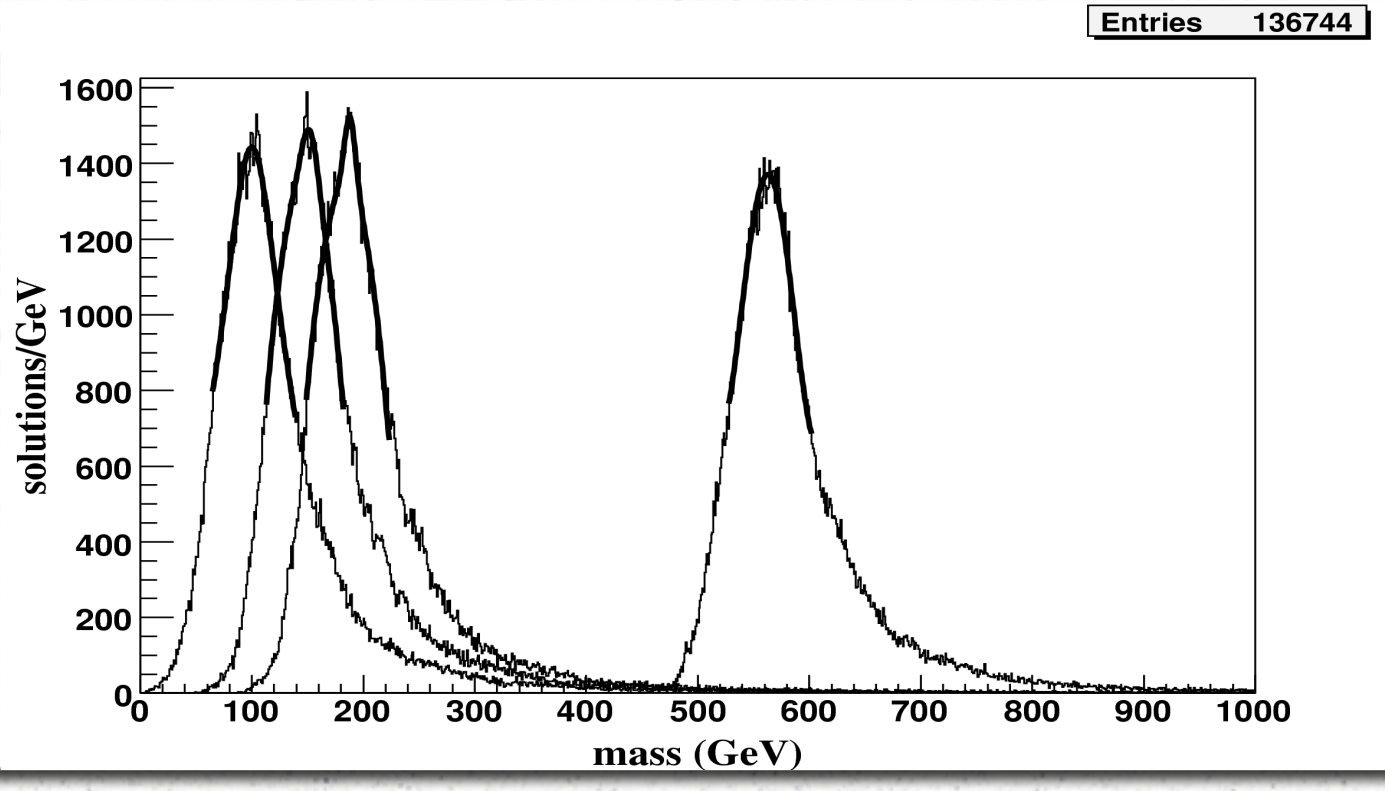
# *Event reconstruct—general consideration*

- Assuming masses are measured
- Reconstruct missing momenta from visible momenta using mass-shell constraints
- System can be under-constrained, exactly solvable or over-constrained
  - Focus on the latter two
  - See Cho, *etal* for under-constrained case (MT2-assisted on-shell reconstruction)

# *Mass determination—an example*

## *(Cheng, Engelhardt, Gunion, ZH, McElrath)*

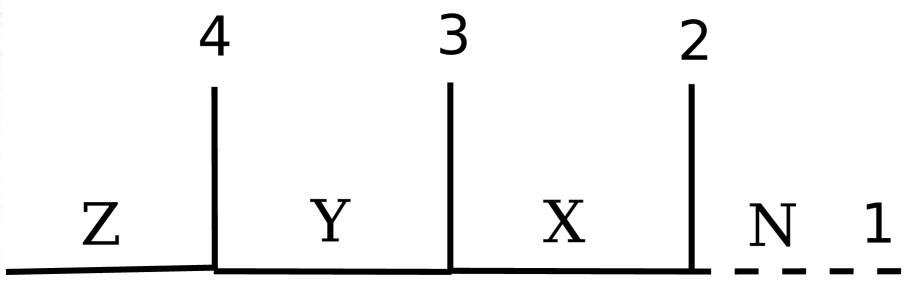
- Using events with two identical decay chains each containing three visible particles.
- Can solve for the masses by combining two events. For a few hundred events in the $\tilde{q} \to q\tilde{\chi}_2^0 \to q\tilde{\ell}\ell \to q\ell\bar{\ell}\tilde{\chi}_1^0$ channel, can determine the masses to the precision of a few GeV.



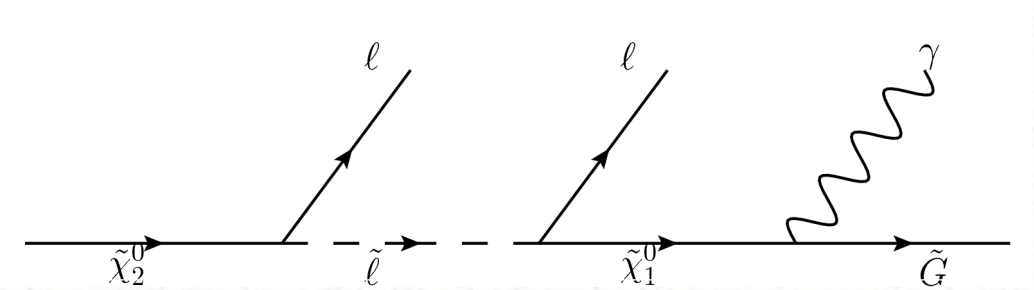
# *Reconstruct the missing particle's momentum --single decay chain case*

- 4 unknowns, 4 equations, we can solve the equations and obtain the missing particle's momentum.

$$p_1^2 = M_N^2$$
$$(p_1+p_2)^2 = M_X^2$$
$$(p_1+p_2+p_3)^2 = M_Y^2$$
$$(p_1+p_2+p_3+p_4)^2 = M_Z^2$$



# *Chargino/neutralino in gauge mediation*

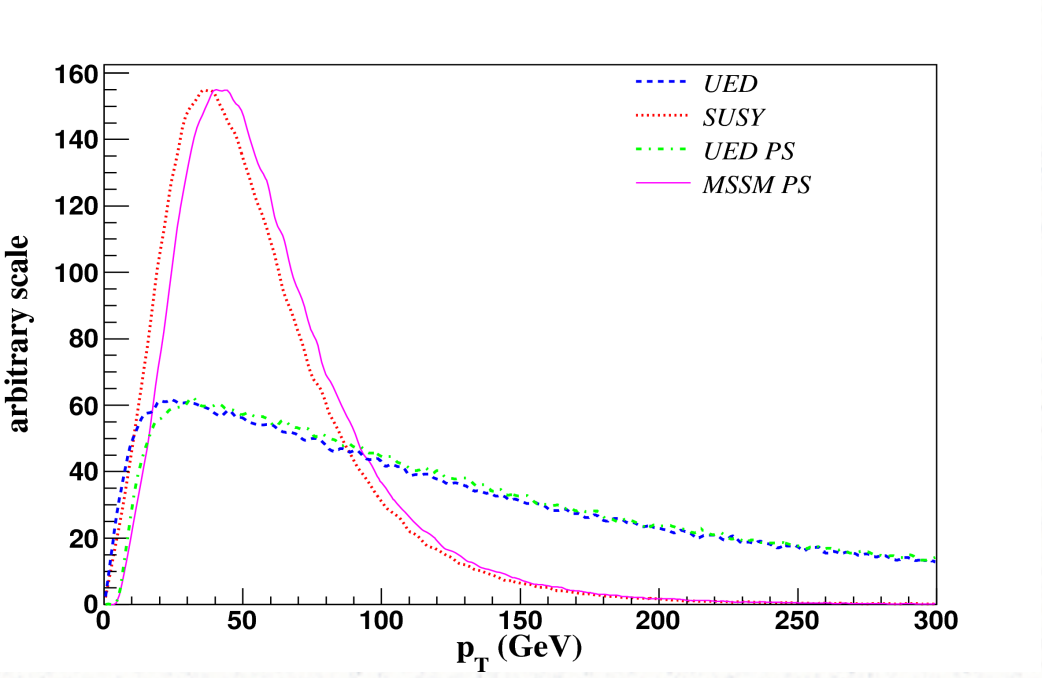



- 2 leptons not enough for reconstruction. Extra photon in gauge mediation.
- Choose masses 181, 143, 97, 0 GeV for both SUSY (SPS1a) and UED (simplified by taking all couplings to be left handed)
- Neutralino 2 decays to dileptons, chargino decays to stau, same decays in UED
- Both neutralino 1 decay to photon+gravitino
- 4-fold combinatoric ambiguity (2 photons, 2 leptons) included

# *Event reconstruction without smearing*

- Event generated with Herwig++ for 14TeV pp
- Correct combination: nsolutions = 200% nevents (quadratic equations)
- Wrong leptons (correct photons): 120%, 121% (MSSM, UED)
- Wrong photons (correct lepton): 70%, 13%
- Wrong photon and wrong lepton: 67%, 12%

# $p_T$ distribution

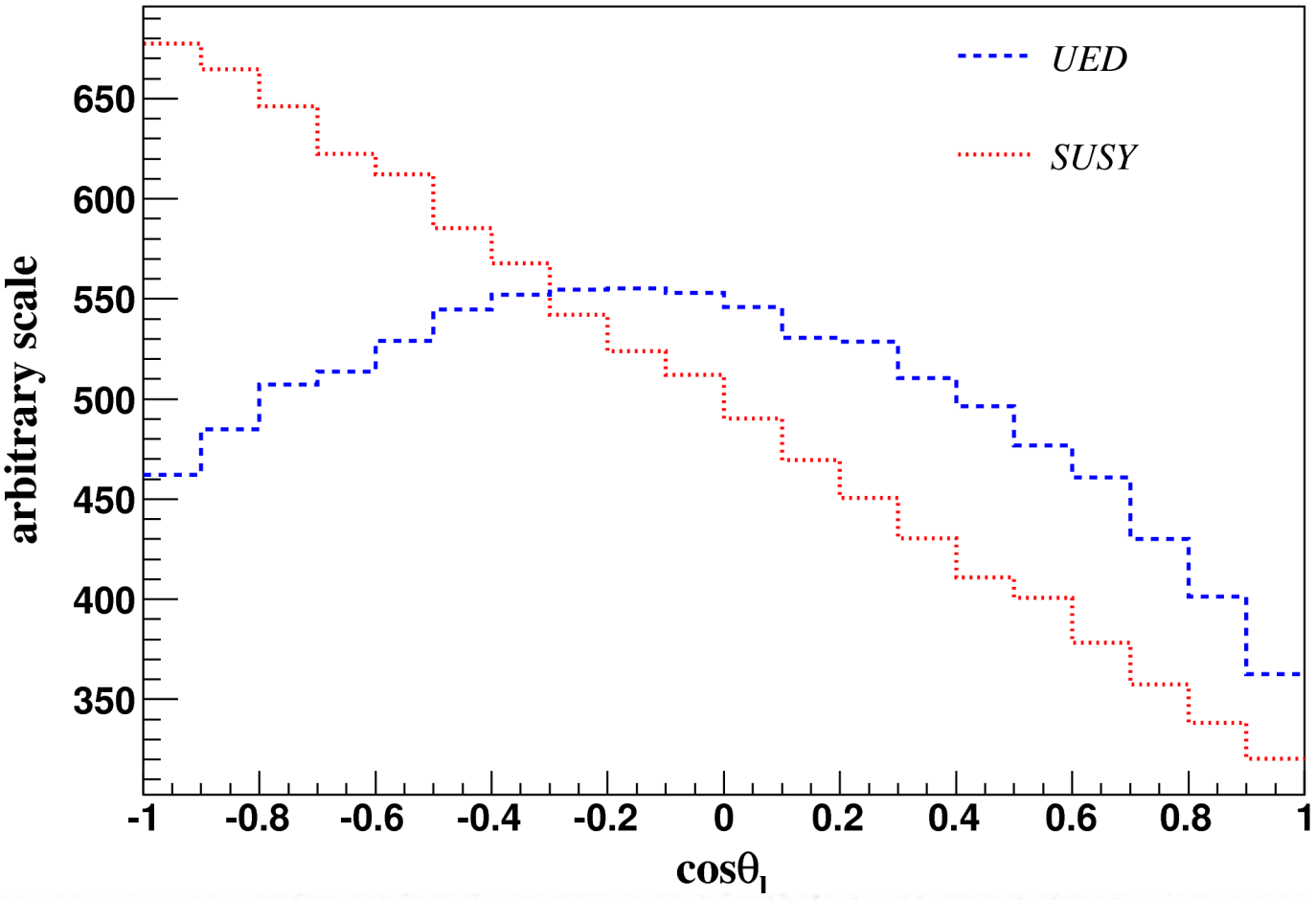



$p_T$ of wrong photon.

PS= phase space decays

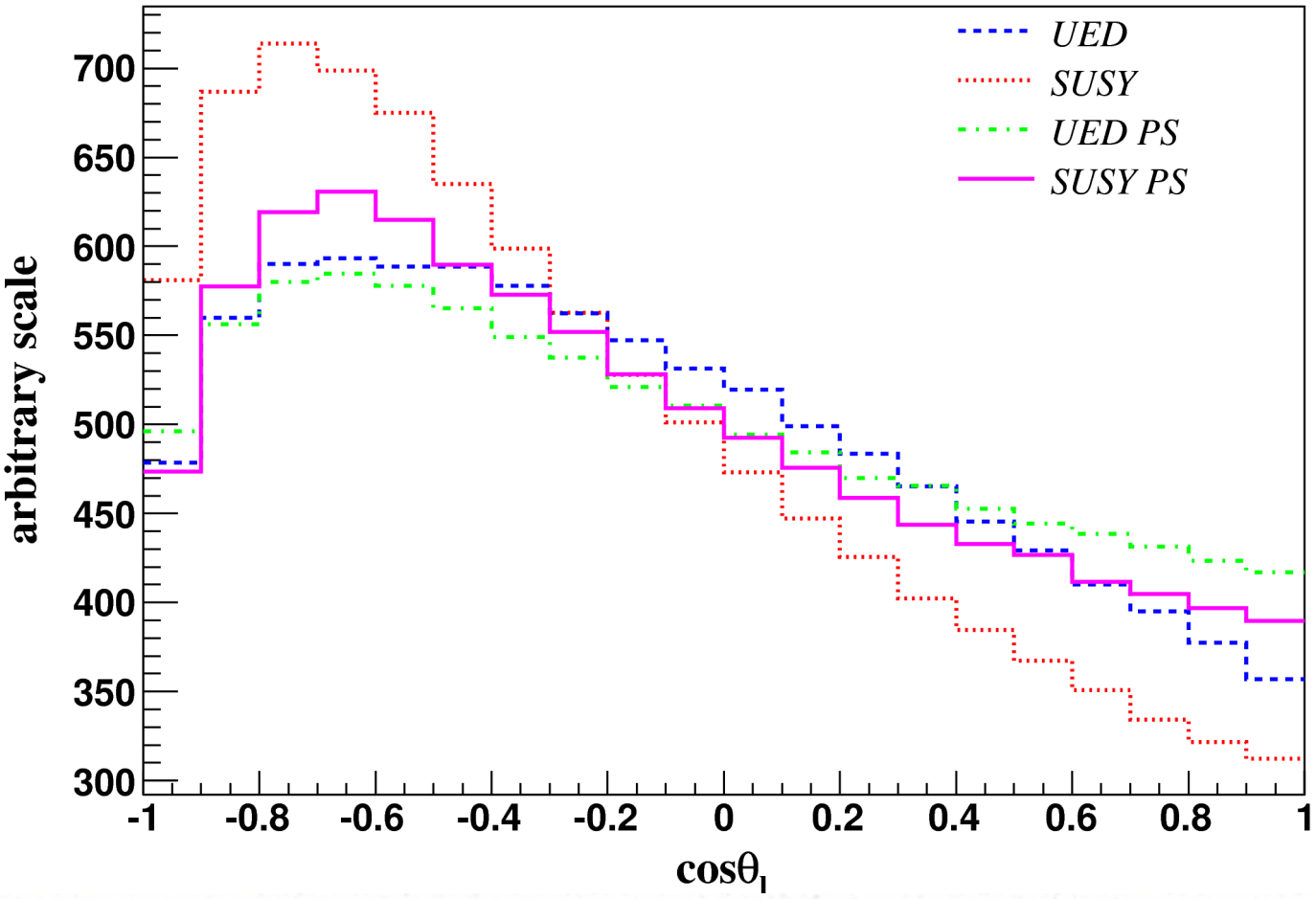
$p_T$ set by 2->2 differential cross-section, insensitive to spin correlation in decays.

# *Polarized neutralino decay*

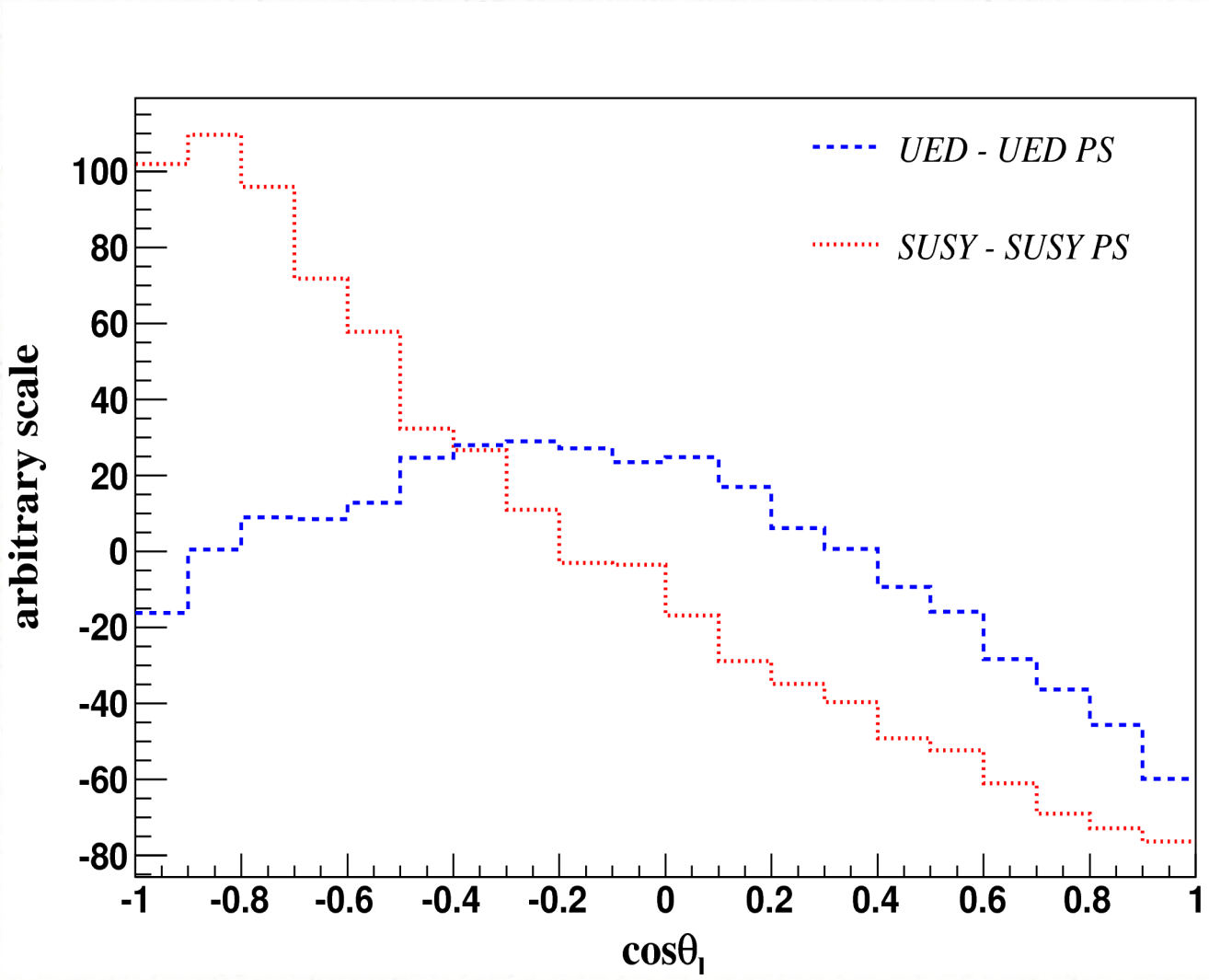



MC

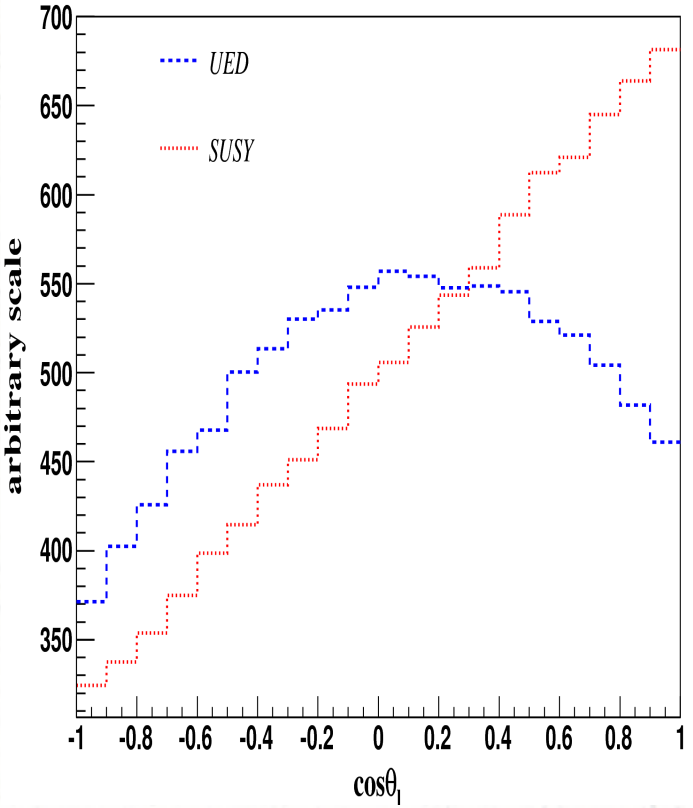
# *Reconstructed distributions*



# *Subtracted from phase space distributions*



# *Leptons of opposite sign*

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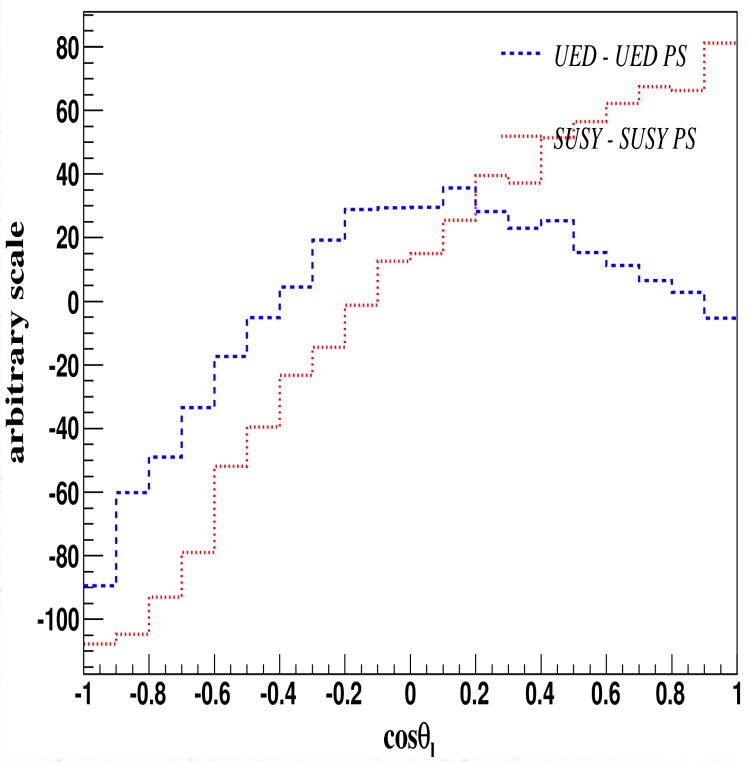



Reconstructed, phase space subtracted

# *Experimental resolution*

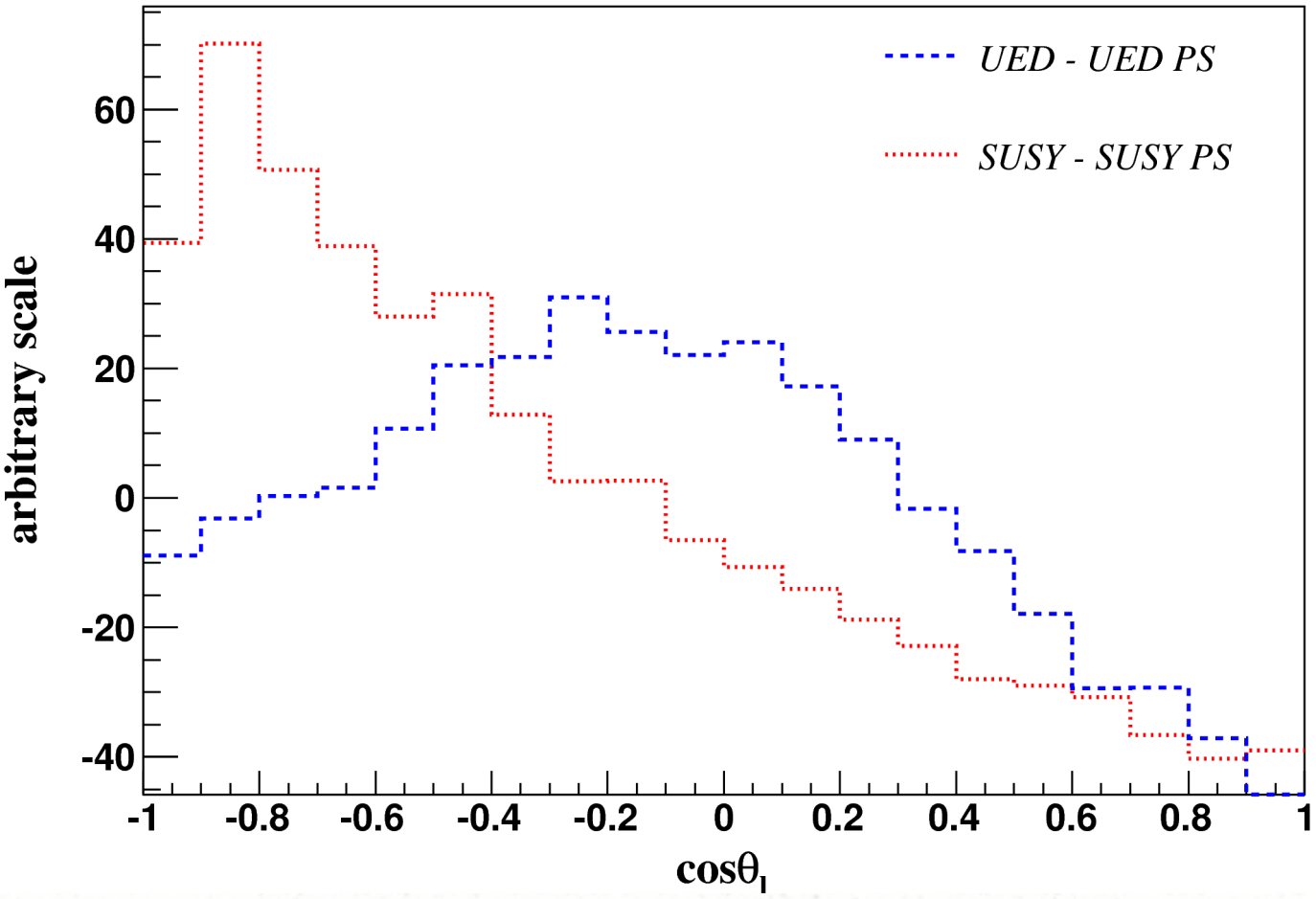
- Leptons

$$|\eta| < 2.4, p_T > 10\mathrm{GeV}$$
$$\frac{\delta p_T}{p_T} = 0.008 \oplus 0.00015 p_T(\mathrm{GeV}),$$
$$\delta\theta = 0.001, \delta\phi = 0.001 rad.$$

- Photons

$$|\eta| < 3.0, \quad p_T > 10\mathrm{GeV},$$
$$\frac{\delta E}{E} = \frac{0.028}{\sqrt{E}} \oplus \frac{0.12\mathrm{GeV}}{E} \oplus 0.0026.$$
$$\delta\eta = 0.001, \quad \delta\phi = 0.003\, rad$$

# *Smeared distribution*

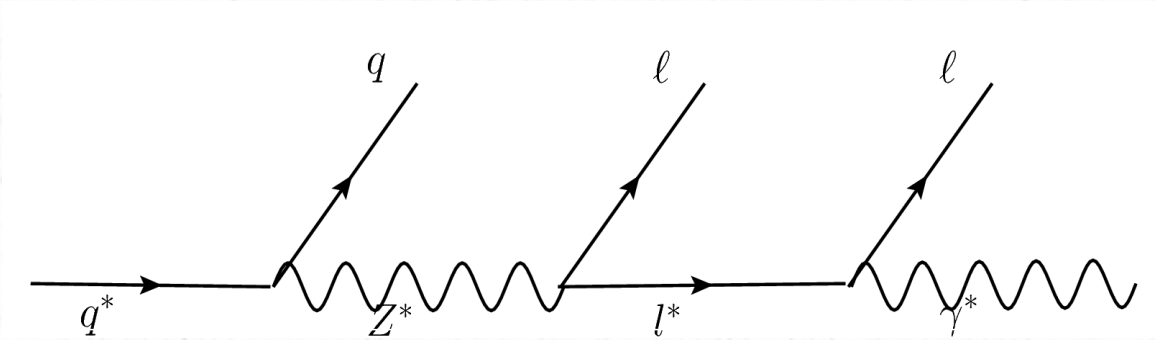



Phase space subtracted

# *Discussion*

- Distributions always contaminated by wrong solutions/combinations
- Need to know what happens in the other decay chain, if particles from the other decay contribute to wrong combinations.
- Visible momentum, masses treated as if exact, didn't use their experimental errors because the system is exactly solvable.  For longer decay chains, likelihood fit using the errors is possible.

# *The KK-quark case?*



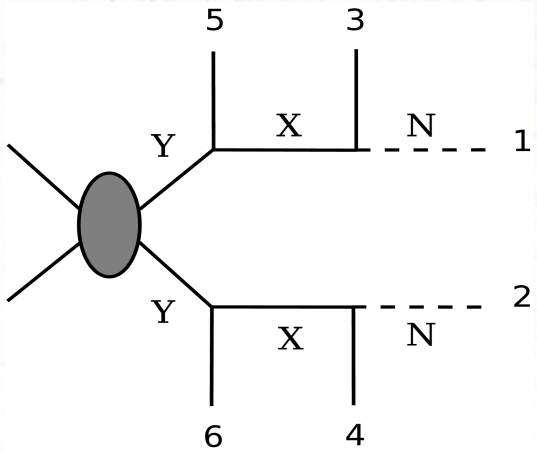

- Squark is scalar, no spin information
- KK-quark is not polarized
- Cannot determine the spin of the first particle in this decay chain using single chain methods--Consider both decay chains

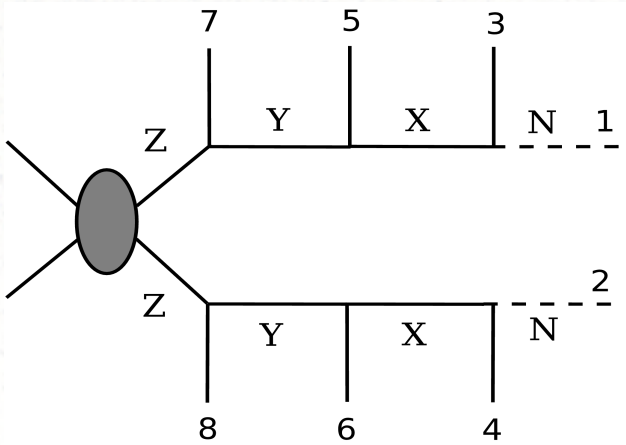
# *General counting of the constraints*

- One chain case: 4 unknowns, *i.e.*, 4-momentum of the missing particle
  - 4 on-shell particles, 3 visible particles: solvable
  - More than 4 on-shell particles: over-constrained
- Two chain case: 8 unknowns
  - 2 extra constrains from measured missing transverse momentum
  - 6 on-shell particles needed to solve, more than 6: over-constrained.

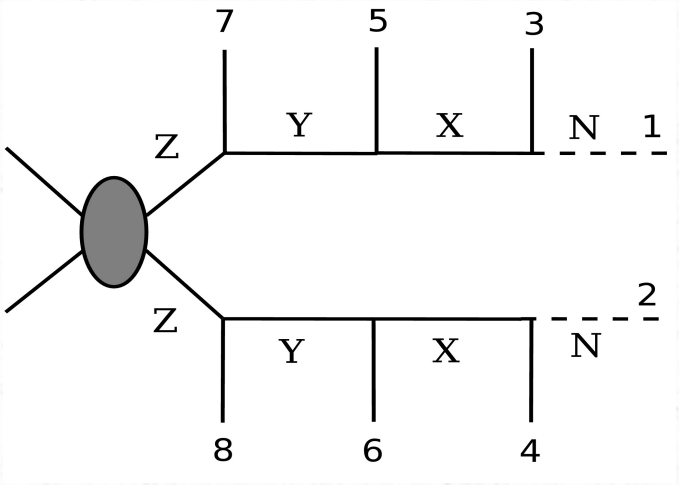
# *Event reconstruction—double chain case*

- Consider events with two identical decay chains (with the same masses)
  - Two visible particles per chain: 8 unknowns, 8 constraints (6 mass shell + 2 transverse momentum), solvable. (ref. ttbar resonance spin, *Bai and Han*)
  - Three visible particles per chain: 8 unknowns, 10 equations, over-constrained. Likelihood fit using experimental resolutions.



# *Over-constrained system*




$$
\begin{aligned}
f_1 &= p_1^2 - m_N^2 \\
f_2 &= (p_1 + p_3)^2 - m_X^2 \\
&\cdots \\
f_9 &= p_1^x + p_2^x - p_{miss}^x \\
f_{10} &= p_1^y + p_2^y - p_{miss}^y
\end{aligned}
$$

- $f_i = 0$ cannot be all satisfied (10 equations, 8 unknowns).

# *Likelihood fit*

- A simplified version:

$$\chi^2 = \sum_i \left( \frac{f_i}{\delta f_i} \right)^2, \quad \delta f_i^2 = \sum_{x=p_{vis},m} \left( \frac{\partial f_i}{\partial x} \delta x \right)^2$$

- Find $p_1$ , $p_2$ that minimize $\chi^2$
- We used a more complicated formalism where the correlations among the equations/measurements are taken into account.

# *Apply to sbottom/KK-bottom pair production*

- Jet resolution

$$|\eta| < 3.0, \quad p_T > 100\mathrm{GeV},$$

$$\frac{\delta E_T}{E_T} = \begin{cases} \frac{5.6}{E_T} \oplus \frac{1.25}{\sqrt{E_T}} \oplus 0.033, & \text{for } |\eta| < 1.4, \\ \frac{4.8}{E_T} \oplus \frac{0.89}{\sqrt{E_T}} \oplus 0.043, & \text{for } 1.4 < |\eta| < 3.0, \end{cases}$$

$$\delta\eta = 0.03, \quad \delta\phi = 0.02 \quad \text{for } |\eta| < 1.4,$$

$$\delta\eta = 0.02, \quad \delta\phi = 0.01 \quad \text{for } 1.4 < |\eta| < 3.0.$$

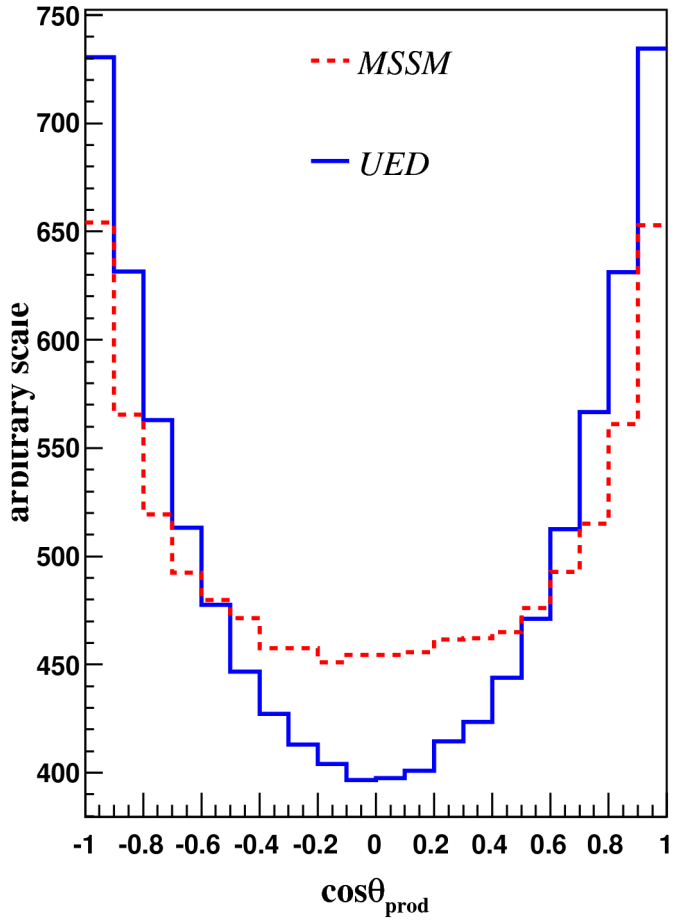
- Lepton resolution as before
- Mass measurements (SPS1a)

$$\delta M_N = \delta M_X = \delta M_Y = 4GeV, \quad \delta M_Z = 6GeV$$

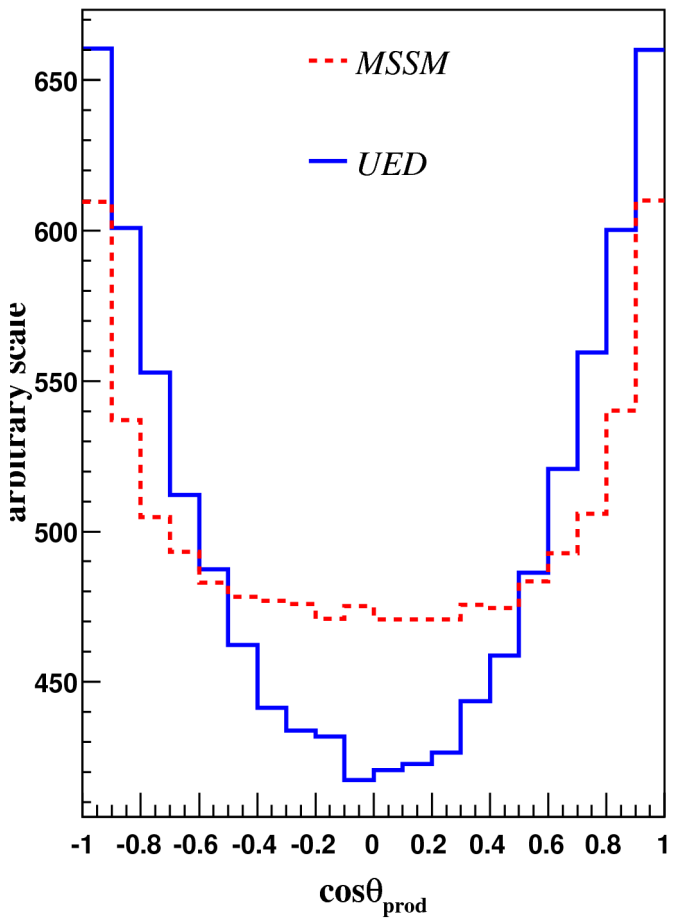
# *Procedure*

- Choose SPS1a and UED with the same spectrum.
- sbottom/KK-bottom pair production (gluino not included). Parton level, 4 leptons + 2 jet, no radiations, momentum smeared by hand.
- For each combination, minimize chi square. Choose the combination that give the smallest chi square. ~30% events get the correct solution.

# *Production angle depends on spin*




MC




Reconstructed

# *Spin correlation between the two chains*

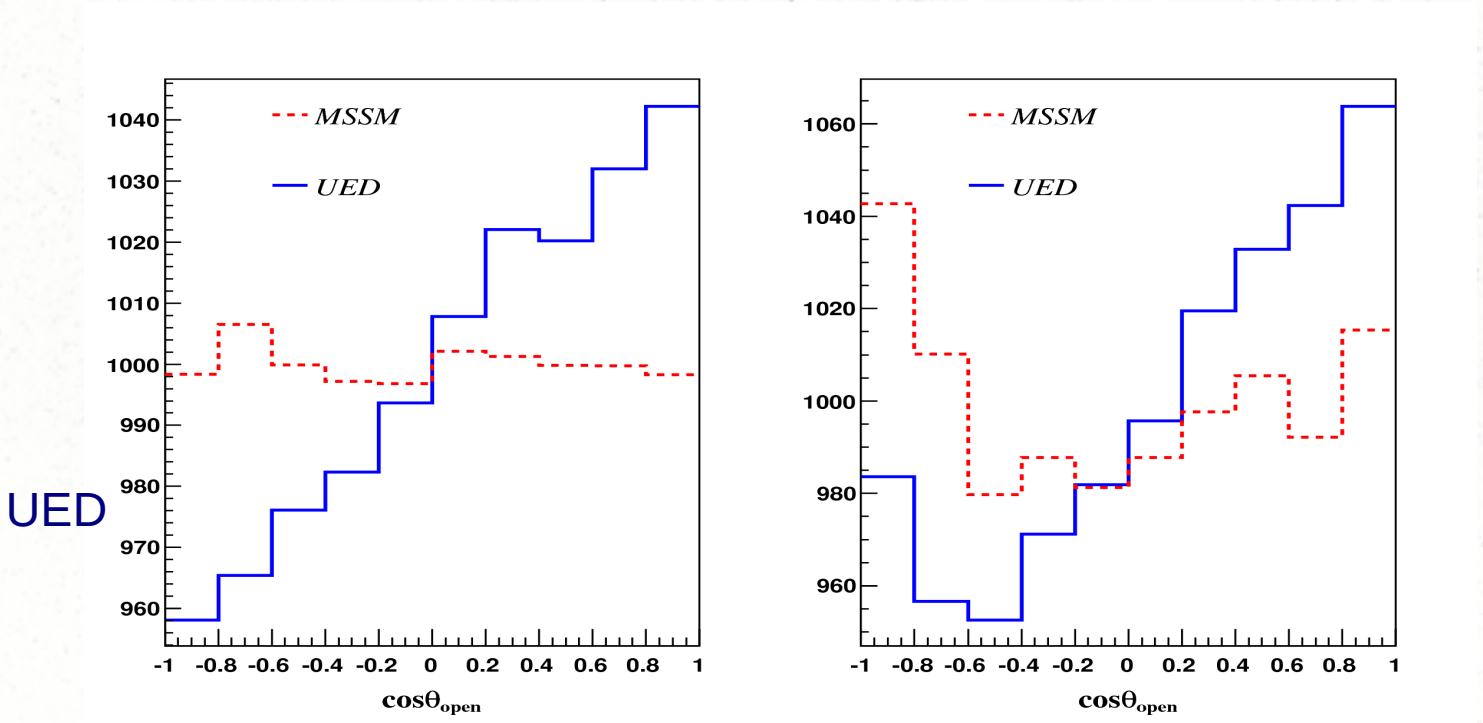
- Squark is scalar, no spin correlation
- KK-quark spin correlated, correlation depends on production(glu/glu vs q/qbar) and CM energy
- Jet-jet opening angle (Boost the jets to their respective mother particle's rest frame, look at the angle between them. )

$$\frac{d\sigma}{d\theta_{open}} = 1 + D\cos\theta_{open}$$

D: constant depending on correlation.

# *Jet-jet opening angle*

- Analogous to ttbar but more difficult: contributions from uubar/ddbar offset glu-glu; decay products massive--Need to optimize the cuts.




MC Reconstructed

# *Conclusion*

- It is often possible to reconstruct the missing particles' momenta if all masses are known—spin is determined in the same way as when all particles are visible.
- We obtain spin information that is only available after event reconstruction.
- Depending on whether the system is solvable or over-constrained, and whether we want to examine a single chain or both chains, apply different methods.

# *Future work*

- Mass and spin measurements at the same time.
- Performance study:
  - What are the good channels?
  - Optimum cuts? Number of events, luminosity needed to distinguish spins?
- Other event topologies.